

Validation of the ASTER thermal infrared surface radiance data product

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ABSTRACT

The Advanced Spaceborne Thermal Emission and reflection Radiometer (ASTER) is a 14 channel high spatial resolution instrument selected for flight on the EOS AM-1 platform. This instrument has a 60 km pointable cross-track swath and five thermal infrared channels between 8 and 12 micrometers with 90 m spatial resolution. Correction for the effect of atmospheric attenuation and emission will be made using a radiative transfer model and atmospheric parameters either from the EOS AM-1 platform instruments MODIS (A40d-mtc-Resolution imaging Spectroradiometer) and MISR (Multi-Angle Imaging Spectroradiometer) or temperature and moisture profiles from global numerical assimilation models. The correction accuracy depends strongly on the accuracy of the atmospheric information used. To provide an objective assessment of the validity of the atmospheric correction *in situ* measurements of water surfaces under a variety of atmospheric conditions will be used to estimate the surface leaving radiance at the scale of an ASTER pixel. The procedure will use an array of continuously recording temperature buoys to establish the bulk water temperature, broadband radiometers to determine the near surface water temperature gradient and radiosonde and sunphotometer measurements and a radiative transfer model to deduce the sky irradiance. These measurements and the spectral emissivity of the water will be combined with the relative system spectral response to provide an estimate of thermal infrared surface leaving radiance for each ASTER thermal channel. An example of this approach using a multichannel thermal aircraft scanner as a stand in for ASTER will be described. It is expected this approach will provide estimates of surface radiance accurate, in temperature terms, to better than 1 K.

KEY WORDS: ASTER, EOS, Thermal Infrared, Atmospheric Correction, Validation, Buoys

1. INTRODUCTION

The objectives of the Advanced Spaceborne Thermal emission and reflectance Radiometer (ASTER) investigation in the thermal infrared includes providing estimates of the radiance leaving the surface. The radiance which is measured by the ASTER instrument includes emission, absorption and scattering by the constituents of the earth's atmosphere. An atmospheric correction procedure will be used to remove these effects providing estimates of the combined radiation emitted and reflected at the surface. Atmospheric correction is necessary to isolate those features of the observation which are intrinsic to the surface, from those related to the atmosphere. Only after accurate atmospheric correction can one proceed to study seasonal and annual surface changes and to attempt the extraction of surface kinetic temperatures and emissivities. Validation of the atmospheric correction procedure is intended to provide an estimate of the uncertainty associated with the correction procedure.

ASTER is one of several instruments to be launched on the NASA Earth Observing System AM-1 platform in 1998 and continues the trend to higher spatial resolution surface imaging begun with the Landsat Thematic Mapper and by SPOT. In addition, ASTER increases the number of channels (14 versus the 7 of the Thematic Mapper and 4 of SPOT). ASTER will provide same-orbit stereo capability by using nadir and aft looking telescopes. It will provide multispectral thermal emission measurements (5 channels) in the atmospheric window region from 8 to 12 μm . ASTER consists of three imaging subassemblies (the VNIR subsystem includes two telescopes for stereo), one in each spectral region: the visible and near infrared (VNIR), the short wave infrared (SWIR) and the thermal infrared (TIR). The nominal size of the instantaneous field-of-view at the earth's surface is 5, 30 and 90 meters in the VNIR, SWIR and TIR respectively, with a cross-track swath width of 60 km for all channels and the instrument has been assigned a data volume equivalent to an 8% duty cycle. The noise equivalent delta temperature performance of the flight ASTER thermal infrared (TIR) channels is 0.3 K or better. At the instrument, the accuracy of measurement expressed as a brightness temperature, is to be 1 K or better in the range 270 to 340 K. The goal of the atmospheric correction procedure is to keep the residual error due to uncompensated effects as low as possible. In most circumstances we would like the residual error to be under 1 K.

2. ATMOSPHERIC CORRECTION PROCEDURE

The approach to be used for ASTER atmospheric correction in the thermal infrared involves two fundamental elements:

- 1) the use of a radiation transfer model capable of estimating the magnitude of atmospheric emission, absorption and scattering and
- 2) the acquisition of all the necessary atmospheric and surface parameters (e.g. temperature, water vapor, ozone, aerosol profiles, surface elevation) at the time and location of the measurement to be corrected.

The radiance leaving the surface, I_{sur} , (which is a combination of both emission and reflection) is related to the radiance derived from the sensor, I_{sat} , the transmission of the atmosphere, T_r , and the atmospheric path radiance, I_{path} , (which arises from both atmospheric emission and scattering) by the following equation:

$$I_{sat} = I_{sur} * T_r + I_{path}$$

The radiation transfer model is used to calculate the atmospheric transmission and path radiance allowing the surface radiance to be determined.

The full-width-at-half-maximum (FWHM) spectral response of the five TIR channels are given in Table 1.

Table 1 TIR channel full-width-at-half-maximum spectral response (μm)

Channel	10	11	12	13	14
Width (FWHM)	8.125- 8.475	8.475- 8.825	8.925- 9.275	10.25- 10.95	10.95- 11.65

MODTRAN (Moderate Resolution Atmospheric Radiance and Transmittance Model) has been selected as the radiation transfer model to be used. MODTRAN^{3,4} traces its heritage back through the several versions of LOWTRAN⁵⁻¹¹.

2.1 Atmospheric parameters

The most important factors in determining the broad band atmospheric transmission and path radiance for the five ASTER TIR channels are the atmospheric water vapor and temperature profiles. Two MODIS clear atmosphere data products are prime candidates: MODIS Temperature Profiles (20 levels, 5 Km spatial resolution); MODIS Water Vapor Profile (15 levels, 5 Km spatial resolution). These two profile products will use NOAA forecast data assimilation model profiles as a base and will modify the assimilation model profiles so that the derived profiles are consistent with the radiances measured by MODIS. Since MODIS will always collect data in the region observed by ASTER, these products should in general be available, for use.

As a backup the assimilation model data itself will be interpolated directly into the ASTER scene. There are two such assimilation systems that will be available: the NOAA global (or for the appropriate areas of North America the regional) assimilation forecast system¹² and the Goddard EOS (GIOS-1) assimilation system¹³. These two systems differ in objective in that the NOAA system is an operational weather forecast system from which profiles could be obtained essentially coincident with the receipt of the raw data from ASTER. The GIOS-1 assimilation system does not have an operational forecast requirement and will be able to wait for all the data needed for assimilation to arrive. Since the processing of ASTER data to radiance will be conducted on a demand basis both of these models could be of use in the absence of profile data from MODIS.

Because of the placement of the five ASTER TIR channels, ozone is not a significant factor in atmospheric correction except for channels 11 and 12 which are the closest channels to the ozone band between 9 and 10 μm . If profile information is available from SAGE (Stratospheric Aerosol and Gas Experiment) during the late 90's it will be used. Since SAGE II or its replacement may not be available at the start of the EOS AM-1 mission we will use the MODIS product O₃ Total Burden (5 Km spatial resolution) with a profile based on climatology. We could also use ozone estimates from TOMS (Total Ozone Measurement System) although they would not be coincident in space and time with the ASTER measurements as is the ozone amount determined from MODIS measurements. In addition, NOAA regularly produces a stratospheric ozone profile product

which could be used. As a backup, if no ozone estimates are available from the same time period as the ASTER measurements, we will use a climatology based on the extensive record from TOMS, SBUV and SAGE.

Like ozone, aerosols will not often limit the accuracy of the atmospheric correction. However, during episodes of high volcanic aerosol loading, they will have an important impact on the radiometry. Both MODIS and MISR plan an extensive set of aerosol data products. We plan to use the MISR data product Aerosol Optical Depth (17.6 Km spatial resolution) to establish the amount of aerosol present. The aerosol composition and particle size distribution will be obtained from the values used by MISR to estimate the optical depth or from the MODTRAN model based on the geographic location of the ASTER scene. The MODIS data product Aerosol Optical Depth, Spectral, is an available backup. In the absence of the MISR or MODIS product over land we will need to develop a compendium of profiles as a function of time of year and geographic location.

Elevation errors contribute to the error in atmospheric correction. Here, an elevation error is defined as the difference between the average elevation of the pixel of interest and the elevation used for that pixel in computing the atmospheric correction. An elevation error can occur either because there is a vertical or horizontal error in the elevation model being used or because the pixel of interest is incorrectly located with respect to the elevation model.

The magnitude of the resulting error in the atmospheric correction depends on the atmospheric profile. (e.g. the amount of water vapor in the profile), the elevation of the surface, the surface temperature and the ASTER channel being corrected.

Currently the only global digital elevation model (DEM) which is available is SRTM30+¹⁴ which has elevations posted every 5 arc minutes (approximately 10 kilometers). This spacing is too coarse to be used with 90 meter ASTER TIR pixels. The EOS Project is developing a plan to provide, by 1998, a near-global DEM with 30 arc second (approximately 1 kilometer) postings based on the Digital Chart of the World (DCW) and other sources¹⁴ and is examining providing data at 3 arc second (approximately 90 meters) postings based on the Defense Mapping Agency's (DMA) Digital Terrain Elevation Data (DTED)¹⁴.

To obtain examples of the magnitude of the atmospheric correction error in relation to the size of the altitude error, the atmospheric correction error was calculated for: five representative atmospheric profiles, all five ASTER TIR channels, every hundred meters from sea level to 5.8 kilometers assuming in each case the altitude error was 100 meters. The maximum error occurs in the shortest wavelength ASTER TIR channel, channel 10 and is 0.28 K in brightness temperature. The maximum error in the least sensitive channels (12 and 13) is 0.08 K. Although the atmospheric correction error is not strictly linear with elevation error, (the maximum error is about 0.3 K per 100 meters of elevation) the linear assumption is reasonably close for elevation errors up to several hundred meters.

For the majority of the earth's surface the existing sources of topographic information (i.e. DCW and DTED) should result in elevation related atmospheric correction errors which are less than a few tenths of a degree Kelvin for the most sensitive ASTER Channel and atmospheric profile (e.g. for the Tibetan region, 50% of the area has slopes less than about 3 degrees¹⁵). In steep terrain (slopes greater than about 30 degrees) it is likely the positional accuracy of both the elevation model and the ASTER pixels will determine the size of the atmospheric correction error and this error could be more than a degree Kelvin in unfavorable cases. Two additional points are also inherent in using an atmospheric profile based atmospheric correction algorithm. First, this method is sensitive to artifacts in the topographic model used. Since global topographic data sets are necessarily large and have been compiled from a variety of sources artifacts are inevitable. It is important to understand and remove these artifacts, where possible, as they will impose systematic errors on the atmospherically corrected brightness temperatures. Second, topographic errors are not spectrally neutral across the five ASTER thermal channels. Methods which use the spectral contrast across these channels to extract additional information should, at a minimum, take into consideration the systematic effect topographic error will have on atmospherically corrected ASTER thermal data.

2.2 Sensitivity to error in the profiles for temperature, water vapor, ozone and aerosols

The accuracy of the atmospheric correction method proposed depends on the accuracy with which the primary input variables can be determined and the sensitivity of the correction to the uncertainty in these input variables. The primary input variables are atmospheric profiles for temperature, water vapor, ozone and aerosols. The sensitivity of the atmospheric correction to uncertainties in the input variables depends on both wavelength (channel integrated values) and the base value for the input variables.

Estimates for this sensitivity were developed using the LOWTRAN 7 radiative transfer model and three of the atmospheres included with LOWTRAN 7. The atmospheres used were Mid-latitude Summer (air temperature at the surface 297.2 K, 2.35 g cm⁻¹ column water amount, 0.332 atm cm total ozone and a "visibility" of 25 km); Tropical (air temperature at the surface 302.7 K, 3.32 g cm⁻¹ column water amount, 0.277 atm cm total ozone and a "visibility" of 25 km) and Subarctic Winter (air temperature at the surface 257.2 K, 0.33 g cm⁻¹ column water amount, 0.376 atm cm total ozone and a "visibility" of 25 km). The sensitivity for each variable, model atmosphere and wavelength was determined by entering a small change in the base value of each of the four primary variables, one at a time, and noting the corresponding change in the calculated radiance. The sensitivity in each of the ASTER channels was obtained by weighting the wavelength dependent sensitivities with an estimate of the expected spectral profile for each ASTER channel.

To illustrate the relationship between uncertainty in the input parameters and the uncertainty in the derived radiance (or its equivalent in brightness temperature) the following uncertainties will be used: 1. Water vapor, 20%, a number near the upper limit accuracy estimate for the MODIS column water vapor abundance determined from thermal infrared measurements; 2. Atmospheric temperature, 0.5% (i.e. -1.5 K), the largest number associated with MODIS atmospheric temperature profile which is in the range estimated for northern hemisphere numerical forecasts of order 1-2 K²; 3. & 4. For ozone and aerosols (expressed as visibility, which is one way aerosol amount is expressed in the LOWTRAN 7 model) the uncertainty was taken as 50% to illustrate the low sensitivity to these variables. The results for three of the five ASTER channels in both radiance and brightness temperature are given in Table 2 for the two most sensitive atmospheres.

Table 2 Percent change in derived radiance as a function of percent change in input parameter

Input Parameter	% Change in Input Parameter	% Change in Derived Radiance* for Tropical Atmosphere			% Change in Derived Radiance* for Mid-latitude Summer Atmosphere		
		Channel 10	Channel 12	Channel 13	Channel 10	Channel 12	Channel 13
Water Vapor	20	4.4 (2.2)	1.8 (1.0)	2.2 (1.5)	2.3 (1.5)	0.9 (0.5)	0.9 (0.6)
Atmospheric Temperature	0.5	-3.5 (-1.8)	-1.5 (-0.9)	-1.7 (-1.1)	-2.3 (-1.2)	-0.9 (-0.5)	-0.9 (-0.6)
Ozone	50	0.2 (0.1)	1.1 (0.6)	0.1 (0.1)	0.1 (0.1)	1.1 (0.6)	0.1 (0.1)
Visibility (Aerosols)	50	0.2 (0.1)	0.4 (0.2)	0.4 (0.3)	0.1 (0.1)	0.5 (0.3)	0.4 (0.3)

* Numbers in parenthesis () are the changes in derived brightness temperature (K) which are equivalent to the percent change in derived radiance.

Because of strong water vapor absorption below 8 μ m, ASTER channel 10 is about twice as sensitive to uncertainties in both atmospheric water vapor and temperature as any of the other four channels. Channel 12 is the most sensitive to uncertainties in ozone because of the presence of part of the 8.5 to 10 μ m complex of ozone bands in this channel. Chess errors (25% in column abundance) in ozone will lead to errors of significance (greater than the instrument's NEAT) for channel 12. Aerosols have some impact on all five channels. The 50% uncertainty used here for visibility could be exceeded if it is necessary to use a climatology based estimate for aerosols. For example, this could happen if a version of SAGE were not in operation and the stratospheric aerosol amount increased due to a volcanic eruption. Increases in tropospheric aerosols will be measured by MISR.

3. ATMOSPHERIC CORRECTION VALIDATION

The overall approach to validation for the surface leaving spectral radiance involves comparison of the surface leaving radiance data product with estimates of the same quantity derived from simultaneous *in situ* measurements and estimates from equivalent MODIS channels.

The uncertainty in the ASTER derived TIR surface leaving spectral radiance has three main sources: 1) the uncertainties in the radiation transfer model (MODTRAN) being used, 2) the uncertainty in the estimates of atmospheric properties used to compute the emission, transmission and scattering of the atmosphere and 3) uncertainty in the on orbit instrument calibration. The sensitivity analysis described above indicates that the expected uncertainty in the atmospheric profiles of moisture and temperature should dominate the overall uncertainty. The purpose of the *in situ* measurements is to insure that sources 1) and 3) above are not dominant and to provide tangible evidence the uncertainty in surface leaving spectral radiance known and is understood. The comparisons with MODIS will be used to provide more frequent estimates of the quality of the product being produced and will allow the exploration of a much wider range of atmospheric conditions than will be possible with *in situ* measurements.

Field experiments have been conducted and are planned at about the rate of two a year, testing aspects of the following approach:

Radiometric measurements from a boat are used to estimate the kinetic temperature of the radiating surface of water areas the size of several ASTER TIR pixels. An array of continuously recording buoys is used to assist in estimating the space and time variation in water temperature. To reduce the radiometric error associated with geolocation error, 3 x 3 pixel areas will be instrumented. Radiosonde profile measurements are used to determine the atmospheric temperature and moisture profiles for use with the radiation model MODTRAN to estimate the spectral sky irradiance. The ASTER spectral response along with the surface kinetic temperature, the spectral emissivity of water and the spectral sky irradiance are used to compute the channel surface leaving spectral radiance which is to be compared with the same quantity from the algorithm being validated. Because of the high emissivity of water and the low value of clear sky irradiance across the spectral interval covered by the ASTER thermal channels *in-situ* estimates of the surface leaving radiance are not very sensitive to errors in the atmospheric measurements (i.e. only the reflected component of the surface leaving radiance is affected).

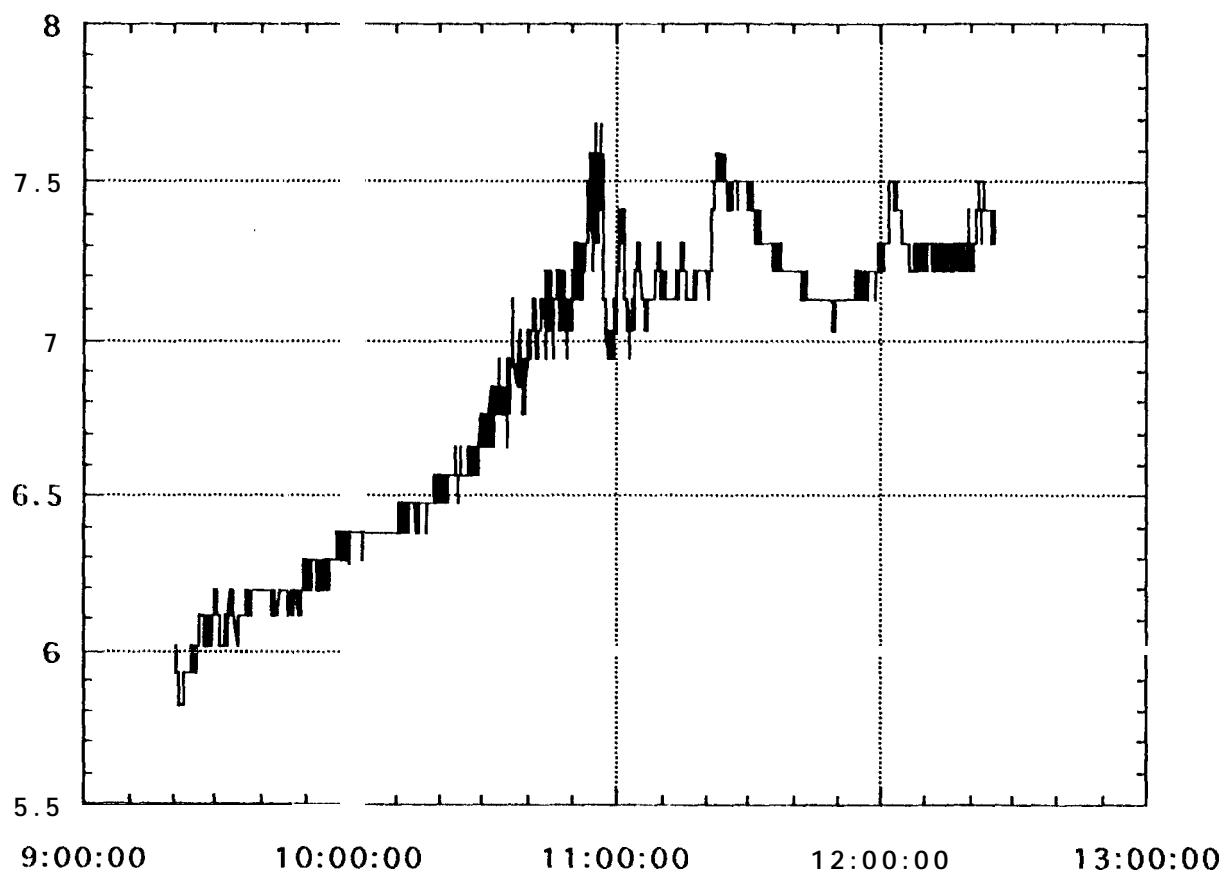
Lake Tahoe and the Salton Sea are being evaluated as sites which provide a range of atmospheric conditions (e.g. warm-wet, warm-dry, cold-wet, cold-dry).

3.1 A field experiment example

Water has been selected as a target because away from shore its surface temperature is relatively uniform in space and time and its spectral emissivity is known and nearly constant. In order to estimate the temperature of an area the size of an ASTER TIR pixel (90 x 90 m) some means of acquiring multiple spatial samples at the time of the satellite overpass is needed. Continuously recording buoys provide one means of providing the space/time sampling needed. In April 1995 this approach was tried at Lake Tahoe in an area 2 km South of Dollar Point using the NASA Thermal Infrared Multispectral Scanner (TIMS) as a stand in for the thermal component of ASTER.

The time history of water temperature at about 1 cm depth for one of the buoys deployed during this experiment is shown in Figure 1.

Figure 1 Buoy #1886 Temperature Reading, Lake Tahoe, 24 April 1995



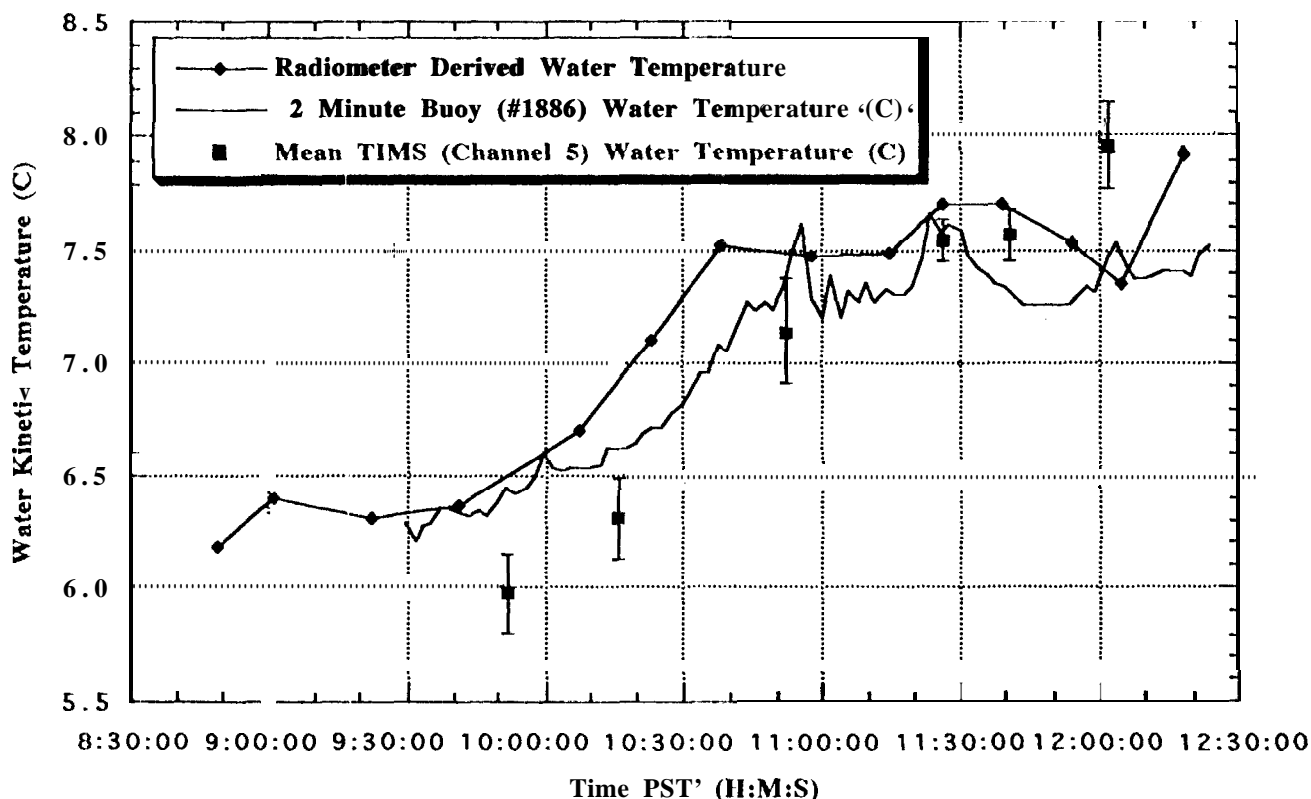
The temperature record of Figure 1 illustrates several features of water temperature behavior which are clearly evident when a continuous record is available. First, a steady increase in water temperature is apparent with the temperature increasing by 1.5 C from 9:30 to 11:00. This is a part of the diurnal variation in near surface temperature. The day was very clear and the air temperature exceeded the water temperature as the day progressed. Second, at several points in this record (e.g. shortly before 11:00 and again at 11:20) the near surface water temperature undergoes a change of several tenths of a degree in a very short period of time (1-2 minutes) as warm (or cold) patches of water form or drift across the buoy's location.

In addition to the buoy measurements, broadband (8-14 μm) radiometer measurements were made of the water surface within 10 m of the buoy #1886 from an anchored boat. Since the radiometer used was known to be sensitive to the environmental temperature, measurements of a field portable water cooled corn blackbody were made before and after each lake temperature measurement. The blackbody was filled with water from the lake which kept the black body temperature within a degree C of the lake water temperature. These in-field calibration measurements were used to correct for any drift in the radiometer over the three and one half hours of measurement.

Atmospheric profiles of air temperature and moisture were acquired from radiosonde flights at the Truckee airport 20 km to the North of the water target area. These measurements along with the spectral emissivity of water were used in conjunction

with MODTRAN to reduce the TIMS thermal imaging data and the radiometer data to estimates of water surface kinetic temperature. These estimates along with two minute averages of buoy #1886 bulk water temperature are shown in Figure 2.

Figure 2 Time History Water Temperature Comparison , lake Tahoe, CA On 24 April 1995



The trend with time of all three measurement types (TIMS channel 5 (10.2-11.1 μm), buoy bulk water temperature and radiometer) is similar. The radiometer and buoy measurements differ by a few tenths degree C as expected since it is common for the radiating skin temperature and the bulk water temperature to differ and the aircraft scanner measurements are on average about 0.4 C cooler than the temperature derived from the *in-situ* radiometer measurements. The six aircraft scanner measurements were acquired over an altitude range of 1.8 to 7.5 km (this corresponds to a nadir pixel size of 4.5 to 19 m) above the lake and no strong trend with altitude was evident.

Viewed as a validation of the atmospheric correction procedure used to correct the aircraft scanner measurements to surface values, the *in-situ* estimation procedure used appears to work to the half degree C level in this example.

4. SUMMARY

A procedure involving *in-situ* measurements of water targets has been developed and tested for use in the validation of the ASTIR thermal infrared surface leaving radiance data product. The results, using a thermal aircraft scanner as a stand in for ASTIR, indicate validation with an accuracy better than 1 C is possible with pixel sizes up to 19 m. Continuously recording temperature buoys provide added confidence that the time and space behavior of the near surface water temperature is understood. Aircraft scanner thermal images of the satellite target area at the time of the satellite overpass would also be useful in establishing the surface temperature pattern.

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